JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
VOL. 36, NO. 2 AMERICAN WATER RESOURCES ASSOCIATION APRIL 2000

# CLIMATE CHANGE IMPACTS ON THE HYDROLOGY AND PRODUCTIVITY OF A PINE PLANTATION[1]

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ABSTRACT: There are increasing concerns in the forestry community about global climate change and variability associated with elevated atmospheric $CO_2$. Changes in precipitation and increases in air temperature could impose additional stress on forests during the next century. For a study site in Carteret County, North Carolina, the General Circulation Model, HADCM2, predicts that by the year 2099, maximum air temperature will increase 1.6 to 1.9°C, minimum temperature will increase 2.5 to 2.8°C, and precipitation will increase 0 to 10 percent compared to the mid-1990s. These changes vary from season to season. We utilized a forest ecosystem process model, PnET-II, for studying the potential effects of climate change on drainage outflow, evapotranspiration, leaf area index (LAI) and forest Net Primary Productivity (NPP). This model was first validated with long term drainage and LAI data collected at a 25-ha mature loblolly pine (*Pinus* taeda L.) experimental watershed located in the North Carolina lower coastal plain. The site is flat with poorly drained soils and high groundwater table. Therefore, a high field capacity of 20 cm was used in the simulation to account for the topographic effects. This modeling study suggested that future climate change would cause a significant increase of drainage (6 percent) and forest productivity (2.5 percent). Future studies should consider the biological feedback (i.e., stomata conductance and water use efficiency) to air temperature change.
(KEY TERMS: climate change; drainage; forest hydrology; loblolly Pine; modeling; PnET-II.)

## INTRODUCTION

There are increasing concerns in the forestry community about global climate change and variability associated with elevated atmospheric $CO_2$ (Michell *et* al., 1990; Groninger *et* al., 1999). According to the projection of several global circulation models (GCMs), by 2100 the global average temperature and precipitation are projected to undergo substantial temporal and spatial changes (McNulty *et al.*, 1997) in the United States. Changes in precipitation and increases in air temperature could impose additional environmental stress on forest growth during the next century. Thus, climate change adds a new dimension to forest management in the next century (Birdsey *et* al., 1995). Because forests cover 55 percent of the southern United States, changes in forest ecosystem structure and functions due to climate change will have significant impact on the environment and social economics in this region.

Loblolly pine (*Pinus taeda* L.) plantations have great influence on wildlife habitat, water quality and water yield, and presently lead timber producers in the U.S., predominating on more than 13.4 million ha of forest lands (Schultz, 1997). Loblolly pines grow rapidly in diverse geographic and climatic conditions with natural range extending from Texas east to Florida and north to Delaware. Forest management practices (i.e., irrigation, fertilization, bedding, drainage) have been intensified on loblolly pine plantations in the last decade to achieve maximum productivity (Albaugh *et al.*, 1998; Campbell and Hughes, 1980). Forest managers are now facing the additional challenge of future climate change to produce more timber in a sustainable way.

A regional assessment of the effects of climate change on forest productivity and hydrology is currently being conducted through the National Global Change Research Program. GIS and a forest process model, PnET-II, are the two major tools for this effort.

[1]Paper No. 99059 of the *Journal of the American Water Resources Association.* Discussions are open until December 1, 2000.
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The model is being tested and validated for selected sites representing the major forest communities in the southern region. The model will be 'scaled-up' to the entire region for climate change impact analysis (McNulty et al., 1997). The PnET-II model was chosen as the primary model because it closely integrates forest biology and hydrology. This integration has been recognized as an *a priori* condition for modeling potential effects of climate change on forest hydrology (Kite, 1998; Heavesley, 1994).

Although the PnET-II model has been well-validated for northern pine and hardwoods (Aber and Federer, 1992; Aber *et al.,* 1995; Aber *et al.,* 1996), it is not known how this model performs for the southern pine forest conditions. Regional applications of this model for southern loblolly pine forest suggested that, in general, the model over-estimated drainage in lower coastal plain forests, such as pine flatwoods systems (McNulty et al., 1996; McNulty *et* al., 1997). Regional model validation for southern pine productivity was not complete 'since only basal area growth, instead of productivity, was used as an index in previous studies (McNulty *et* al., 1996). The model has not been validated with site-specific, watershed or field scale forest hydrologic and productivity data sets for loblolly pine forests.

This paper reports a simulation study using data collected from a small forested watershed on a flat lower coastal plain in North Carolina. The long-term (1988-1997) forest hydro-meteorological and tree growth records from this site provided an opportunity to comprehensively validate the model for both hydrology and productivity components. This paper first presents model validation procedures and results, then discusses implications of one climate change scenario to loblolly pine plantations based on model simulations.

## METHODS

### *Study Site and Data Collection*

The study site is located in Carteret County on the eastern North Carolina coast. The site has a flat topography ( < 0.2 percent) with a dynamic shallow groundwater water table (0-3 m below land surface) in poorly drained sandy loam soils. Average available soil water for the O-100 cm soil layer at field capacity (i.e., Soil Water Holding Capacity) was estimated as about 25 cm with an average soil porosity of 40 percent. This drained experimental watershed has an area of 25 ha with an average elevation of 3 m above sea level. The watershed boundary was defined by one road and two parallel ditches about two meters in depth. Loblolly pine trees were planted in 1974 *on* the watershed, commercially thinned in 1980 and 1983, and fertilized in 1981 and 1989. Since 1988 this watershed has been intensively monitored for climate, groundwater table, and drainage outflow. Leaf area, nitrogen concentration and forest growth data have been collected on a monthly or annual basis (Amatya *et al.,* 1996) and are summarized in this paper for model testing and validation. Annual net primary productivity (NPP) for stem wood was determined from annual stem volume increase estimation by destruction harvesting methods. Stem density was determined as 0.5 $kg/m^3$.

### *The PnET-II Model*

The PnET-II model was originally developed for studying forest ecosystem processes in northern forests (Aber and Federer, 1992). It is a lumped parameter, monthly-time-step model of carbon and water balances. It simulates both carbon and water cycles in a forest ecosystem using simplified algorithms that describe key biological and hydrologic processes. Input parameters for vegetation, soil and site locations, and climate may be derived from the literature or measured from a local study site. Stand level vegetation parameters include those regulating the physiological and physical processes such as photosynthesis, light attenuation, carbon allocation, and rainfall interception. Only one soil parameter, soil water holding capacity (field capacity in percentage x rooting depth), is required. Climate input data include minimum and maximum air temperature, photosynthetic active radiation (PAR), and total precipitation (Figure 1). The hydrologic cycle is simulated by the water balance equation. The input component of soil water storage is represented bv net precipitation (i.e., precipitation-canopy interception), and outputs consist of canopy interception, plant transpiration, fast or macro-pore flow representing water not available for extraction by plant roots, and lateral and deep drainage. Soil evaporation is neglected in fully stocked forest ecosystems. Evapotranspiration is defined in this article as the sum of plant transpiration and canopy interception. Water yield or drainage is defined as the sum of lateral and deep seepage. The model assumes that water that is not subjected to evapotranspiration eventually flows to streams as runoff. Transpiration is directly linked to forest photosynthesis and forest carbon gain processes by modeling transpiration as a function of water use efficiency and vapor pressure deficit. Therefore, PnET-II closely integrates forest hydrology with the biological processes, This integration is essential for

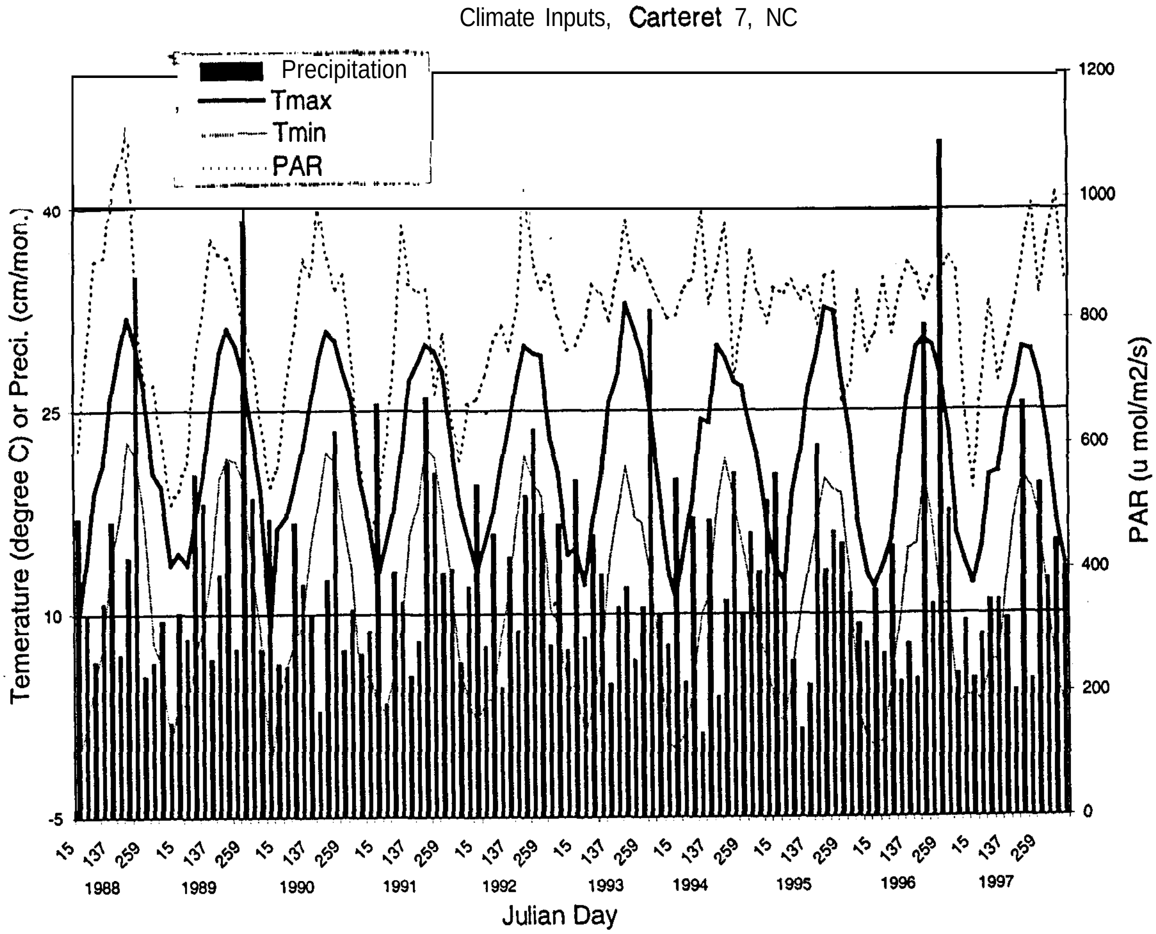


Figure 1. Climate Inputs Required by the PnET Model.

predict climate change effects on biology-dominated systems, such as forests (Kite, 1998).

Because there *were* no detailed physiological measurements for the vegetation parameters at the study site, most of the input parameters for the PnET-II model were derived from an extensively measured loblolly pine site in the Sandhills of Scotland County, North Carolina about 150 miles west of the Carteret County (Table 1). Compared to the coastal plains, this site is relative dry and nutrient poor (Albaugh et al., 1998). Parameters listed in Table 1 represent the most sensitive and often site/species specific ones in modeling forest hydrology and productivity on a stand level. As described previously, the study site is quite flat and surface overland flow rarely occurs until the entire soil profile is saturated. Drainage outflow generates from subsurface shallow groundwater and moves slowly. This hydrologic system is largely different from what the PnET-II was originally designed for, such as the hilly regions, where drainage develops from deep seepage from subsurface soils and water movement is mainly driven by gravity due to sloping. Therefore, when applying PnET-II to the coastal areas with periodical high water table, modification of the original concept of drainage generation concepts is needed. For flat landscape, it is the entire soil water storage that controls drainage. For example, surface water can be stagnant or moving very slowly in pine flatwoods and plants have the potential to extract water deeper than 100 cm. In such case, the Water Holding Capacity (WHC) parameter should be set . much larger than the value measured from soil samples and defined in PnET-II.

### *Climate Change Scenarios*

Climate is expected to change both in space and time throughout the earth. This change is complex and there is no consensus as how each climatic variable, especially precipitation, will be affected. Compared to the.CGCM1 (Canadian Climate Change Model 1), HADCM2 climate change scenario generated by the Global Circulation Model (GCM) at the Hadley Center in United Kingdom was used in our

TABLE 1. Critical Input Parameters for Modeling Loblolly Pine Ecosystems by the PnET-II Model.

| Parameters Description | Parameter Abbreviation | Value for Loblolly Pine Stand |
|---|---|---|
| Intercept of the Regression Relationship Between Max. Photosynthesis and N Concentration (n mol $CO_2$/g leaf/sec.) | AmaxA | 1.92 |
| Slope of the Regression Relationship Between Max. Photosynthesis and N Concentration (n mol $CO_2$/g leaf/s/percent of N) | AmaxB | 39.64 |
| Optimum Air Temperature (°C) | PsnTOpt | 28 |
| Percent Foliage N Concentration (g N/g leaf) | FolNCon | 1.29 |
| Specific Leaf Weight (g/projected $m^2$ leaf) | SLW | 210 |
| Half Saturation Light Level (μ mol/$m^2$/s) | HalfSat | 291 |
| Light Extinction Coefficient | K | 0.46 |
| Growing Degree Days for Leaf to Start Crowing (°C) | GDDFolStart | 900 |
| Growing Degree Days for Leaf to Stop Growing (°C) | GDDFolEnd | 3000 |
| Foliage Retention Time (year) | FolReten | 2.0 |
| Water Use Efficiency Constant (mg C/g $H_2O$) | WUE | 11.2 |
| Soil Water Holding Capacity (cm) | WHC | 20 |
| Canopy Interception/Evaporation Fraction | PrecIntFrac | 0.15 |

simulation as a conservative prediction for the effects of changes of air temperature and precipitation in coastal North Carolina (Kittel *et al.*, 1997) (Figure 2). For the particular site in this study, according to HADCM2, by the year 2099, average maximum air temperature will increase by 1.6 -1.9°C, minimum temperature by 2.5-2.8°C, and precipitation by 0-10 percent varying from season to season (Figure 3). Compared to the average national level, the predicted changes in the three variables at the study site are moderate. We used these deviations and variations as the basis to project future climate change from the normal conditions. Normal conditions were defined as the baseline climate observed at the study site during 1988-1997.

## RESULTS

### *Model Validation*

As mentioned earlier, the forest stands were thinned in 1988 and the weir was manipulated for water control adjustment in 1988 and 1989, and thus those two years were not appropriate for model validation purposes. Because the PnET-II model is not designed for non-closed canopy conditions, predicted hydrology and productivity were compared to measured data only for the years from 1990 to 1997. Data and simulation for year 1988 and 1989 are useful to show management effects and tree development. Significant portion of the PAR and minimum air temperature data (day 166 to 267) were not available for 1994, so data from year 1993 were used for this period assuming the two years had similar climate pattern. However, annual comparison for productivity for 1994 was not included since the missing data might cause great errors in the productivity component.

Annual drainage outflow predicted by the PnET-II model compared well with the measured data ($r^2$ = 0.70, slope of the liner regression equation = 0.967, in 19.. = 0 0019 n = 8). The over prediction for runoff at ... and 1989 was properly caused by the fact that the weir at the watershed outlet was raised resulting in less outflow (Figure 4). On average, over the years during 1990-1997, simulated annual runoff was ... cm, which was about 0.5% higher than the measured average. A pair t-test suggests there was no significant difference between simulated and measured annual drainage (p = 0.7). The prediction error was acceptable.

Simulated annual evapotranspiration ranged from 97 cm to 108 cm, which are within

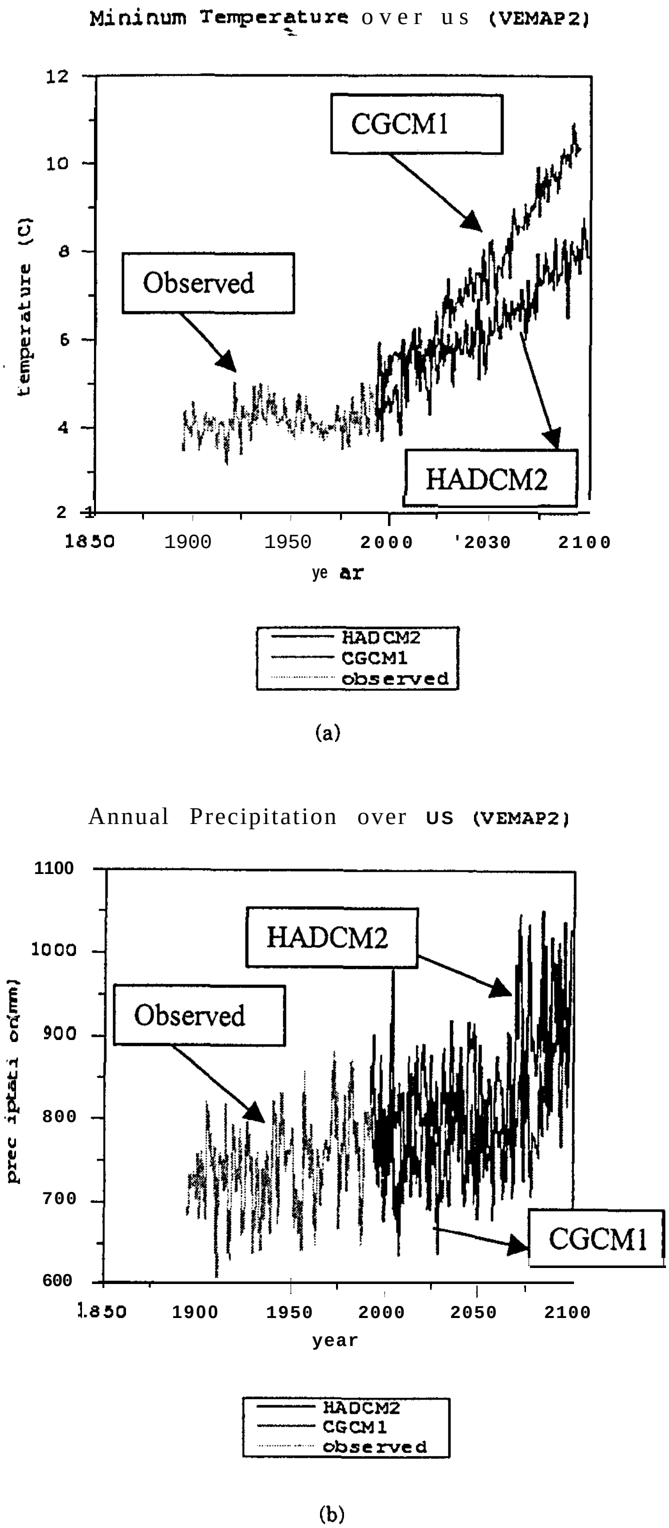


Figure 2. Observed and Predicted Variability of Average Minimum Air Temperature (a) and Precipitation (b) Across the United States. HADCM2 and CGCM1 represent the climate change scenarios predicted at the Hadley Climate Center in UK and the Canadian Climate Center, respectively.

magnitudes as simulated by the forest hydrology model, DRAINMOD, using the Penman-Monteith method (McCarthy et *al.,* 1991) (Figure 5). On average, approximately 32 percent of annual precipitation becomes drainage, while 68 percent of precipitation returns to the atmosphere as evapotranspiration for the forested watershed in this study. On an eight-year average, PnET-II had almost identical prediction of 102 cm/year for ET to the value estimated by the DRAINMOD model.

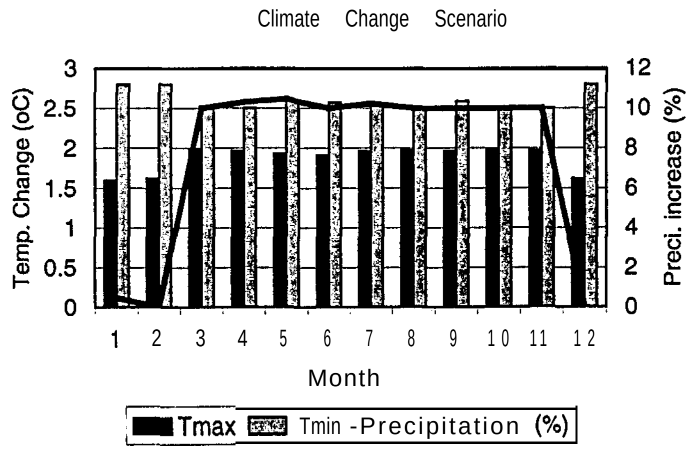


Figure 3. Precipitation and Air Temperature Change Scenarios for the Study Site in Eastern North Carolina as Predicted by HADCM2.

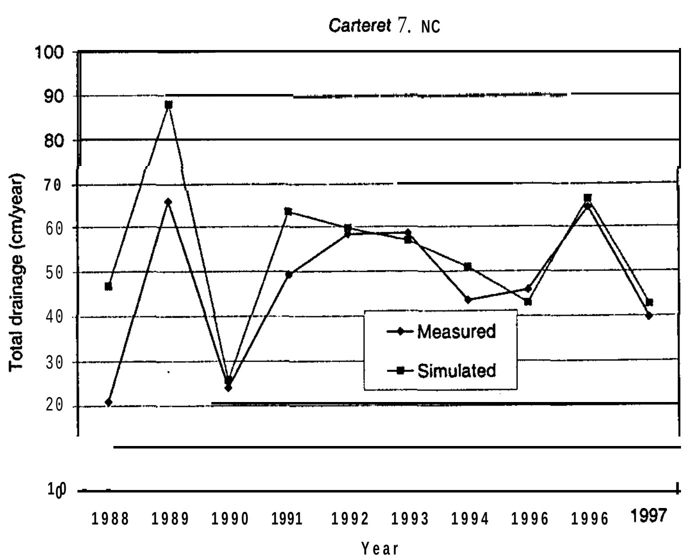


Figure 4. PnET-II Validation for 10-Year (1988-1997) Annual Drainage Outflow.

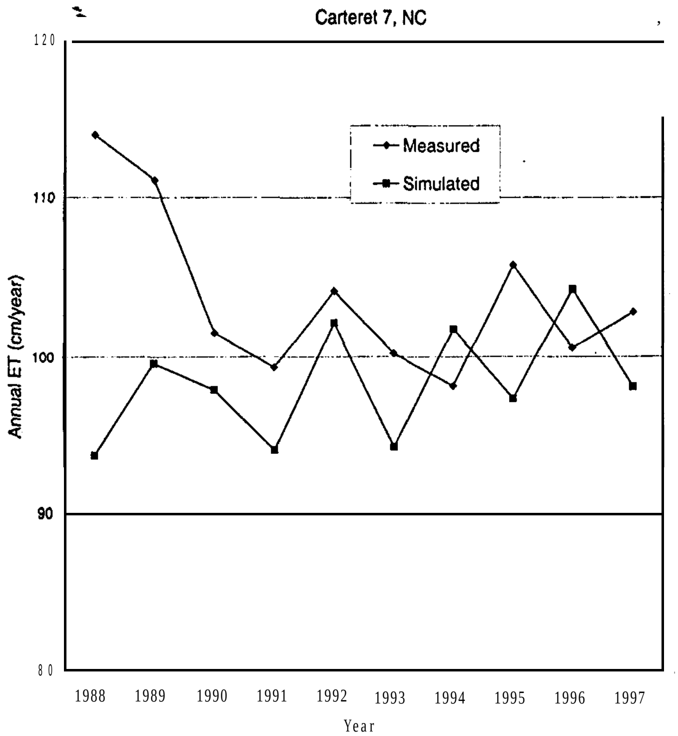


Figure 5. PnET-II Validation for 10-Year (1988-1997) Annual ET.

The PnET-II model gives only total NPP (Net Primary Productivity) for wood and does not differentiate between stem wood and branch wood. So, direct comparison between stand stem wood NPP, that was available from field estimation, and predicted NPP is not an option. We derived stand total NPP from measured NPP for stem wood (Weyerhaeuser Co., unpublished data). Albaugh et al. (1998) found stem wood NPP for fertilized loblolly pine stands was about 37 percent of stand total NPP. Based on this value we estimated the total NPP varied from 2240 $g/m^2$ to 2740 $g/m^2$ per year with an average of 2490 $g/m^2$/year. In general, predicted annual NPP follows the trends of estimated from the field. On an average, the model only over estimated total NPP by 1 percent (Figure 6). A pair t-test did not detect statistical difference between simulated and measured total NPP during 1990-1997 except for year 1994 ($p = 0.7$). The dramatic decrease in predicted total NPP in 1994 (no shown in Figure 6) probably did not occur in reality as shown by the flat line of measured NPP during 1993-1995. This discrepancy was believed to be caused by the input climate data of PAR and air temperature.

The model overpredicted somewhat annual average LAI during 1991-1992, when the stand canopies were presumably closed by the age of 18 (Figure 7). This discrepancy may be caused by several reasons: (1) the model overestimated foliage mass albeit predicting total NPP reasonably; and (2) the factor to convert foliage mass to LAI or specific leaf weight (SLW) was uncertain.

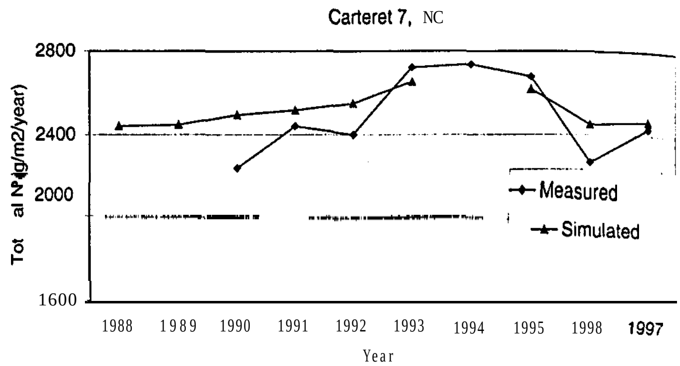


Figure 6. Comparison Between Predicted Annual NPP and Estimated Total NPP Derived from Stem Wood Volume Increase Data.

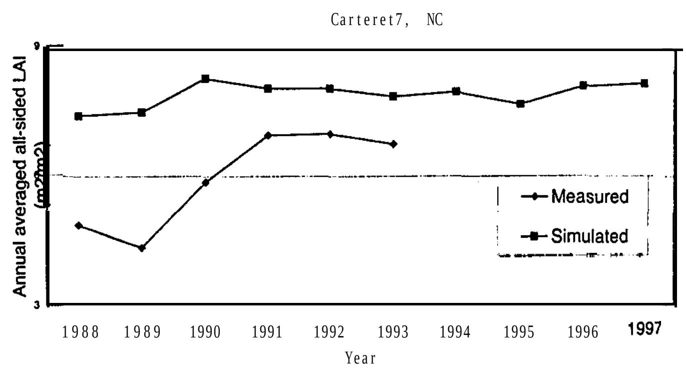


Figure 7. PnET Validation for Annual Leaf Area Index (data for year 1988 and 1989 are not applicable for comparison purposes).

***Effects of Climate Change on Hydrology and Productivity***

The model was rerun by using the same set of parameters of the lo-year base line, but with a new climate scenario of increased air temperature and precipitation as described previously. We assumed the same leaf nitrogen concentration and water use efficiency values as the baseline period even though those two critical parameters may change in response to global air temperature and water availability The simulation predicted that climate change would result in a significant (paired t-test, $p = 0.0019$, $n = 10$) 6 percent increase in drainage (Figure 8), a significant 8.7 percent (paired t-test, $p < 0.001$, $n = 10$) increase in ET, and a significant (paired t-test, $p <$

0.001, n = 10) 2.5 percent increase of total productivity (wood + leaf + root NPP) (Figure 9). The magnitude of increase in forest drainage is some what less than potential increase in precipitation of 10 percent. The additional water is consumed by tree growth since forest productivity is expected to increase by 2.5 percent. Although the site had a seasonal shallow water table, increase in precipitation may improve soil moisture conditions during the drought period in early spring and sometimes in the summer months. The air temperature increase results in an increase in available beat and an improved condition for photosynthesis of loblolly pine plantations.

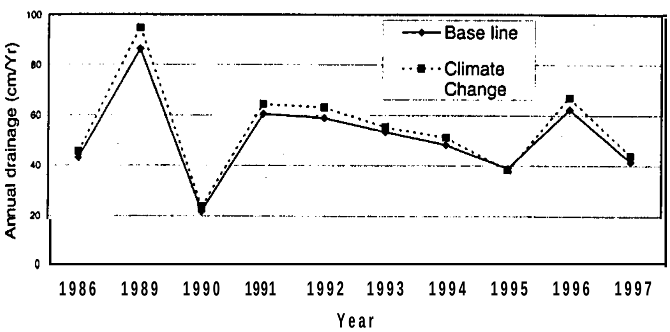


Figure 8. Effect of Climate Change on Annual Drainage from a Loblolly Pine Plantation in North Carolina.

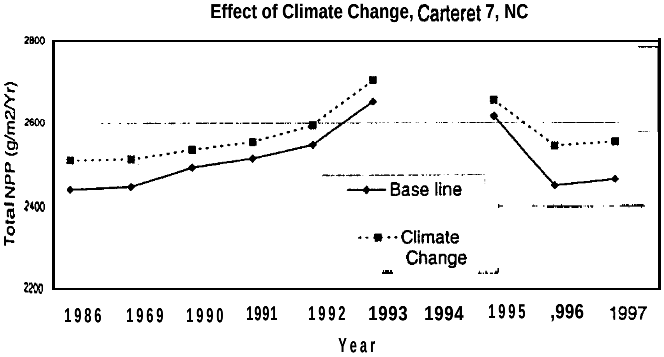


Figure 9. Effect of Climate Change on Forest Total NPP of a Loblolly Pine Plantation in North Carolina.

## CONCLUSIONS

The PnET-II model developed for northern forest ecosystems was validated and applied to a southern drained pine system. The model was parameterized using detailed physiological data from a nearby site. Simulated drainage outflow, ET, and total NPP compared favorably to measured experimental data. However, the model overestimated LAI, suggesting possible predicting errors in the relative carbon allocation among foliage, stem, branch, and root tissues, Model validation for individual components is needed. Such research is critical for studying the forest ecosystem responses to nutrition gradients in regional applications.

In the coastal regions of the eastern US, mature loblolly pines rarely show water stress on the wet soils under current baseline climate conditions. Water was found not to be a limiting factor for tree growth even under the HADCM2 scenarios. Forest productivity and water use are expected to increase significantly, but drainage is not expected to decrease dramatically due to possible increases in precipitation in the next century Compared to other studies for the entire southern U.S., this study suggested that climate change would have relatively less effect on pine ecosystems in the North Carolina coastal region (McNulty et al., 1997). However, future studies should consider biological, responses (i.e., stomata conductance, water use efficiency) to air temperature change and $CO_2$ concentration.

## ACKNOWLEDGMENTS

The authors thank J. D. Aber for assistance in model use. This study was partially supported by the National Institute for Global Change and the Southern Global Change Program, USDA Forest Service, Raleigh, North Carolina. The authors also thank three anonymous reviewers for valuable comments to improve the early version of the manuscript.

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